IBIMA Publishing
Communications of International Proceedings
https://ibimapublishing.com/p-articles/44ICT/2024/4454324/
Vol. 2024 (23), Article ID 4454324

# Optical Digital Communication System in Open Space Without Own Electromagnetic Emission*

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* Presented at the 44th IBIMA International Conference, 27-28 November 2024 Granada, Spain

## Abstract

UAV (Unmanned Aerial Vehicle) communication in operational conditions requires reliable, safe and undetectable solutions. Traditional radio systems are susceptible to interference, and optical FSO (Free-Space Optics) technologies require complex beam control mechanisms, which limits their use in lightweight UAVs. The key motive of the study was to develop a new communication system that minimizes these limitations, improving the safety and efficiency of transmission. The literature indicates a lack of solutions that would combine the advantages of FSO technology, such as high throughput and resistance to electromagnetic interference, with the possibility of use in lightweight UAVs without heavy control mechanisms. The gap primarily concerns the lack of technology enabling emission-free communication, which would be both simple to implement and adapted to changing weather conditions. As part of the study, an innovative system based on a piezoelectric optical modulator was developed. The methodology included designing and analyzing the possibilities of a modulation system based on an optical cone with variable geometry. The system works by illuminating the UAV with a laser beam from a ground station, which is modulated and reflected back, eliminating the need for the UAV to emit its own radiation. Theoretical analyses of the communication range and the effect of wavelength on transmission efficiency were conducted. The results indicate that the system can reach significant distances. The solution is characterized by high resistance to detection and interference, making it a promising direction for the development of FSO technology for UAVs.

**Keywords:** free space optical, modulating retroreflector, corner cube retroreflector

## Introduction

Communication between the ground station and the UAV is a key element of the effective operation of UAV platforms on the modern battlefield. Providing a stable, reliable and secure data link in difficult conditions, such as electromagnetic interference, jamming attacks or the need to hide the location by minimizing revealing emissions, requires the use of various advanced technologies. The most commonly used solution is RF radio communication - Radio Frequency. Traditionally, communication between the ground station and the UAV is carried out on radio waves, both in the L, S, C, X and Ku, Ka bands. Radio communication offers wide availability, ease of implementation and a relatively large range. In turn, for light UAVs, frequencies in the UHF bands are used, which provide adequate data throughput. However, RF communication in UAV systems is associated with many limitations, the most critical of which are: interference and jamming attacks, i.e. deliberate interference of the radio signal, which can prevent communication and lead to the destruction of the UAV. Another problem is electromagnetic interference (EMI) - especially in crowded frequency bands, it can cause interference, reducing the signal quality and causing unwanted emissions that can reveal the presence of UAVs. To minimize the described problems, various techniques are used to optimize the quality of communication. In RF systems, communication channels are divided into FDMA

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**Cite this Article as:** Krzysztof SZAJEWSKI, Tomasz PAŁYS and Anna SZAJEWSKA, Vol. 2024 (23) “Optical Digital Communication System in Open Space Without Own Electromagnetic Emission " Communications of International Proceedings, Vol. 2024 (23), Article ID 4454324, https://doi.org/10.5171/2024.4454324

(Frequency-Division Multiple Access) frequency bands, TDMA (Time Division Multiple Access) time windows, frequency hopping - a technique that allows randomly changing the frequency band, reducing the risk of interference. The spread spectrum method CDMA (code-division multiple access) is effective in hiding electromagnetic emissions. The use of a spread spectrum signal makes it difficult to detect and jam the signal, because the signal power is spread over a larger bandwidth. However, there are methods for jamming it CDMA (Chang 2021). Regardless of the encoding method, the digital signal is then encrypted with a block or stream cipher, which makes it impossible for the adversary to read it. The introduction of an additional index in each block prevents data injection into the transmission channel, which prevents the UAV from taking control of the control channel. Modern communication technologies for unmanned aerial vehicles are increasingly turning to alternative solutions, such as hybrid optical communication RF-FSO (Samimi 2013, Erdogan 2022, Wondmagen 2024) and purely optical communication FSO (Al-Gailani 2021), which is highly resistant to radio interference and has high throughput. FSO uses light (including infrared) as an information carrier. Since the data link involves a point-to-point connection, there is no problem of bandwidth congestion in FSO, especially since the width of the occupied channel is limited only by the spectrum width of the laser or LED used. Figure 1 shows the most commonly used RF radio transmission coding methods and a view of the occupied bandwidth in relation to FSO communications.

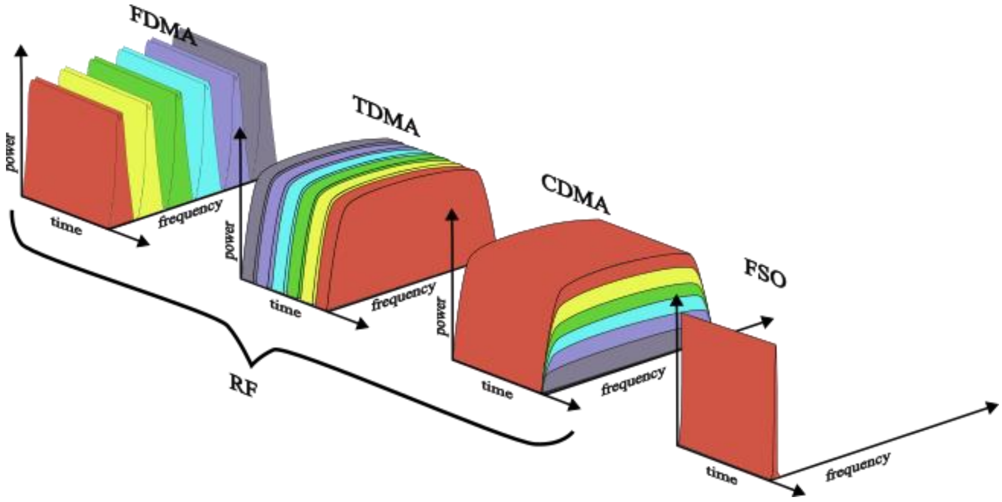

**Fig. 1. Comparison of the occupied band in RF and FSO**

*Source: own elaboration*

Standard FSO communication methods that are carried out in the line of sight require the use of relatively heavy optical beam guidance mechanisms, which complicates their application in lightweight UAVs (Fraire 2024). Most of the development work related to mobile FSO is related to high-speed railways (HST), where the use of high-bandwidth RF technology poses many problems (Al-mohammed 2024). One of the beam positioning technologies is guidance using piezoelectric actuators. The literature (Claeyssen 2022) describes in more detail different methods of guiding the laser beam. FSO has many advantages, but it also has some disadvantages compared to RF. Table 1 shows the most important differences between FSO and radio communication.

**Table 1. FSO Communication Features with Respect to RF in UAV Transmission Applications**

| Advantages | Disadvantages |
|---|---|
| Lack of licenses and regulations for using the visible and infrared passband | Communication limited to line of sight (LOS) |
| High data throughput | High impact of weather conditions on signal propagation (rain, fog, snow) |
| No impact of RF interference because FSO does not use radio waves, it is resistant to jamming | Need to use mechanical beam guidance in the case of mobile devices |
| no interference | No ability to overcome obstacles |
| Increased security - it is difficult to intercept the FSO signal, and its directionality reduces the risk of detection and interception of the transmission | High dependence of the operating distance on weather conditions |
| Low power consumption | High impact of vibrations on the positioning of the light beam |
| No influence of own relative speed to the base station on signal quality | - |

*Source: own elaboration*

The need to search for alternative communication methods led to the development of the described solution, in which the UAV does not emit any radiation and does not require precise control of the light beam. The concept is to illuminate the UAV with a beam of radiation from the base station. This beam is then modulated and reflected towards the ground station using a piezoelectric modulator, which operates on the principle of a moving optical cone with variable geometry.

## Implementation

The presented solution is a continuation of earlier works described in (Szajewski 2024). The construction of an optical piezoelectric modulator is presented below. The modulator consists of three mirrors mounted orthogonally to each other, creating an optical cone. The mirrors are supported on piezoelectric microactuators (figure 2).

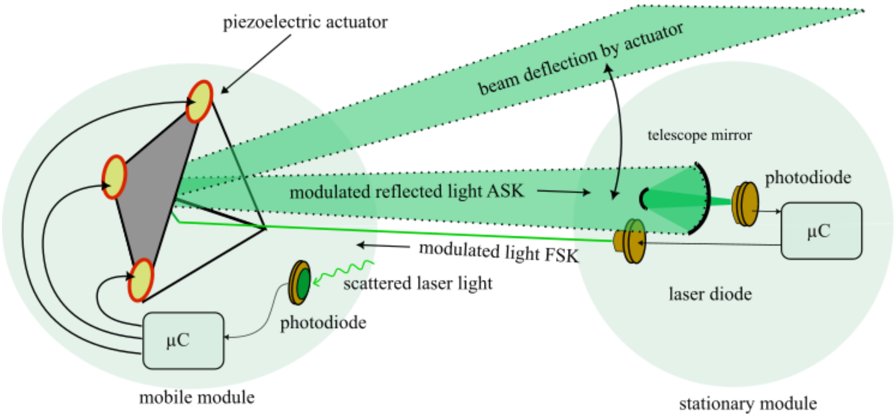

**Fig. 2. FSO Communication Concept using a piezoelectric modulator**

*Source: own elaboration*

By changing the voltage on the piezoelectric, small changes can be made to the position of the mirror in the modulator. These changes cause the laser beam, whose source is the ground station, not to be reflected in the same direction from which it came. Thanks to this, the photodiode on the receiver side does not detect the return beam. Since the projected laser beam has a Gaussian distribution on the perpendicular plane, digital transmission modulated with ASK (Amplitude Shift Keying) can be realized by moving the mirror. The operating frequency is limited by the physical size and mass of the mirror and the properties of the piezoelectric itself. The deflections of the mirror depend on the applied voltage. In the prototype, three small piezoelectrics with primary acoustic purpose, each with a diameter of 10 mm, were used to support one of the mirrors. The mirrors are vapor-deposited and made in the form of circles with a diameter of 25 mm. A view of the modulator prototype is shown in figure 3.

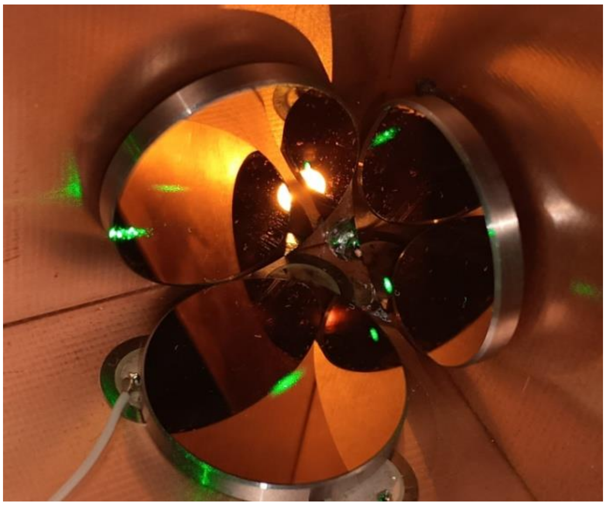

**Fig. 3. Interior view of the piezoelectric modulator prototype**

*Source: own elaboration*

Communication can also take place in full-duplex mode, because the beam sent from the base station can be modulated at a higher frequency with FSK modulation. The next part of the work focuses on the theoretical possibilities of using the modulator in terms of the distance between the UAV and the base station.

## Results

In order to investigate the theoretical communication range, a simplified formula was established, the theoretical analysis of which of the SFO system operation range is determined by the ratio of the signal power reaching the photodetector (Iphoto) to the dark current level according to formula 1.

$$I_{photo} > I_{dark} \tag{1}$$

The parameters of the analyzed FSO system are presented in Table 2. In the analyzed example, the detector was a PIN diode with the symbol BPW 21 and an observation telescope with a mirror diameter of 20 cm.

**Table 2. FSO system parameters**

| **Parameter** | **value** |
|---|---|
| laser power in the base station $P_{laser}$ | 0.05W |
| source beam diameter (beam waist) $\boldsymbol{w_0}$ | $1 \times 10^{-3}$ m |
| laser wavelength λ | $5.5 \times 10^{-7}$m |
| laser beam divergence | Gaussian |
| modulator surface $A_p$ | $4.9 \times 10^{-4}$ m$^2$ |
| light reflection coefficient in the modulator $\boldsymbol{\eta}$ | 0.8 |
| telescope mirror diameter $D_t$ | 0.2 m |
| detector sensitivity S (λ= 550 nm) | 11 nA/lux |
| detector dark current $I_{dark}$ | 2 nA |

*Source: own elaboration*

The detector current depends on the radiation power, the mirror area ($A_{det}$) in the telescope and the distance L (formula 2). In the considerations it was assumed that the detector has the diameter of the telescope mirror and its sensitivity was reduced by the reflection coefficient in its concave mirror. The power reaching the detector was determined by formula 2.

$$P_{det} = P_{laser} \cdot \eta \cdot \left[1 - exp\left(-2\frac{A_{det}}{\pi w(L)^2}\right)\right] \tag{2}$$

where: w(L) is the laser beam with a Gaussian distribution at a distance L described by formula 3. In the analysis for each plane perpendicular to the propagation axis, the beam along the axis has a Gaussian distribution.

$$w(L) = w_0\sqrt{1 + \left(\frac{\lambda L}{\pi w_0^2}\right)^2} \tag{3}$$

Then, the detector current was determined, which depends on the sensitivity and power of the incident radiation and the luminous efficiency, according to formula 4.

$$I_{det} = P_{det} \cdot K_\lambda \cdot \frac{S}{A_{det}} \tag{4}$$

where: luminous flux Φ and intensity E [lux] were determined based on formulas 5 and 6.

$$\Phi = P_{det} \cdot K_\lambda \tag{5}$$

$$E = \frac{\Phi}{A_{det}} \tag{6}$$

Figure 4 shows the estimated current generated on the photodiode. Assuming perfect visibility, the Idet current drops to the noise level at a round trip distance of 55.6 km (from laser to modulator and back to detector). Thus, the maximum theoretical distance in vacuum is approximately 27 km for a wavelength of 550 nm. The estimated current for three wavelengths of visible radiation is also shown. The distance analysis does not take into account atmospheric attenuation, the strength of which depends on atmospheric conditions.

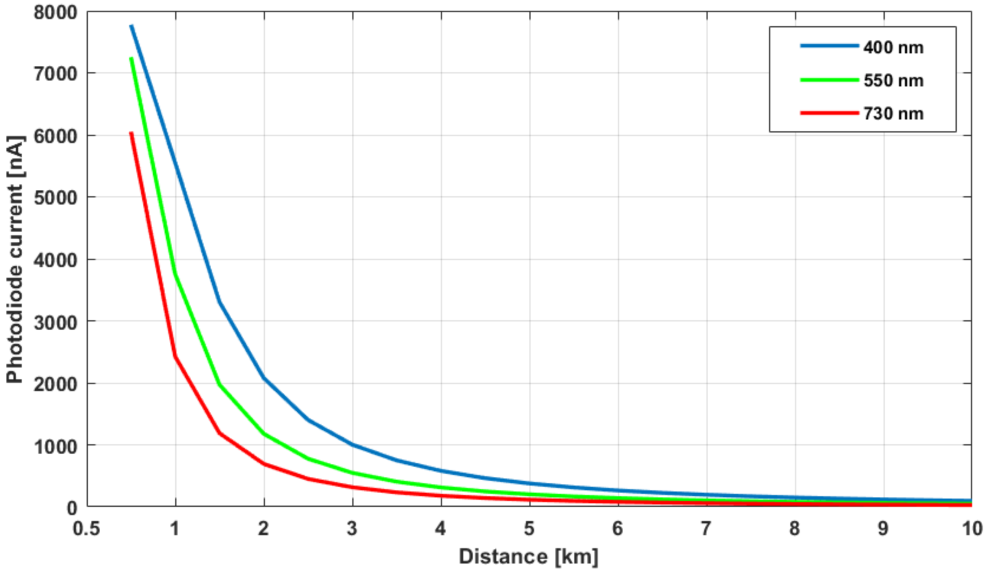

**Fig. 4. Dependence of the photodiode current on the laser wavelength**

*Source: own elaboration*

Figure 5 shows an enlarged fragment of the graph from figure 4 for distances above 5 km, which shows the strong influence of wavelength on distance.

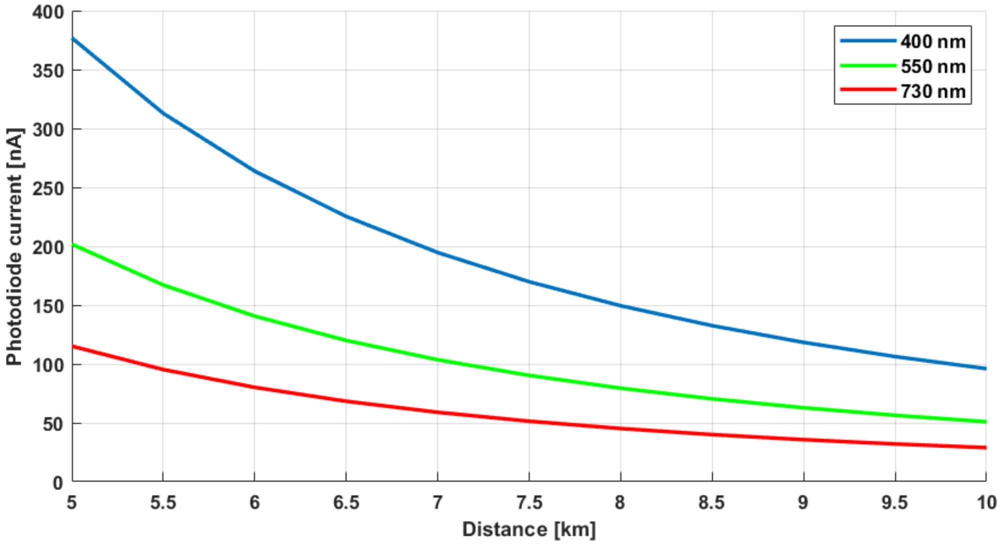

**Fig. 5. The influence of wavelength on the PIN photodiode current**

*Source: own elaboration*

Table 3 shows the degree of attenuation of 550 nm wavelength light by the atmosphere, depending on the prevailing atmospheric conditions (Weichel 1990).

**Table 3. Visible light attenuation depending on the prevailing atmospheric conditions**

| **Atmospheric conditions** | **attenuation [dB/km]** | **visibility [km]** |
|---|---|---|
| good visibility (at least 10 km) | 0,2 | > 10 |
| thin fog | 2 | 4 |
| light fog | 4 | 2 |

|  |  |  |
|---|---|---|
| dense fog/light snow | 10 | 1 |
| dense snow | 25 | 0.2 |

*Source: own elaboration*

## Conclusion

The conducted research on the FSO optical communication system for UAVs indicates the key role of laser wavelength parameters in optimizing the system performance. On the one hand, shortening the wavelength reduces the beam divergence, which allows for more precise light direction and an increase in the range of effective communication. On the other hand, longer wavelengths better penetrate atmospheric obstacles, such as fog or dust particles, whose size is smaller than the wavelength. Therefore, the choice of the laser wavelength should be adapted to the operating conditions, taking into account both divergence and atmospheric attenuation. The research also indicates the need to dynamically adjust the mirror deflection amplitude in the piezoelectric modulator depending on the distance between the base station and the UAV. As the distance increases, precise modulation requires smaller mirror deflections to ensure correct reflection and modulation of the beam. This necessity results from the geometric requirements of optical beam propagation in FSO systems. The research results highlight the potential of the proposed system, but also indicate the need for further optimization in terms of wavelength, modulation and adaptation of parameters to changing atmospheric and operational conditions.

## Acknowledgment

This work was financed/co-financed by Military University of Technology under research project UGB 702/2024

## References

- Al-Gailani S. A. et al., "A Survey of Free Space Optics (FSO) Communication Systems, Links, and Networks," in *IEEE Access*, vol. 9, pp. 7353-7373, 2021, doi: 10.1109/ACCESS.2020.3048049.
- Al-Mohammed H. A., Yaacoub E., Abualsaud K. and Al-Maadeed S. A., "Using Quantum Key Distribution With Free Space Optics to Secure Communications in High-Speed Trains," in *IEEEAccess*, vol. 12, pp. 43560-43574, 2024, doi: 10.1109/ACCESS.2024.3380015.
- Chang X., Li Y., Zhao at al. "A Scattered Wave Deceptive Jamming Method Based on Genetic Algorithm against Three Channel SAR GMTI," *CIE International Conference on Radar (Radar)*, Haikou, Hainan, China, pp. 414-419, 2021, doi: 10.1109/Radar53847.2021.10028041.
- Claeyssen F., Aigouy G., Betsch E., Barillot F., Maillard T. and Pages A., "Fast & fine Steering Mirrors based on piezoelectric & magnetic actuator technologies for Air & Space," *ACTUATOR 2022; International Conference and Exhibition on New Actuator Systems and Applications*, Mannheim, Germany, 2022, pp. 1-6.
- Erdogan E, Altunbas I, Kurt G. K. and Yanikomeroglu H., "The Secrecy Comparison of RF and FSO Eavesdropping Attacks in Mixed RF-FSO Relay Networks," in *IEEE Photonics Journal*, vol. 14, no. 1, pp. 1-8, Art no. 7901508, Feb. 2022, doi: 10.1109/JPHOT.2021.3127397.
- Fraire J.A, Ruiz-de-Azua J. A. and Fernandez-Nino E., "Towards Optimal Placement of Free-Space Optical Terminal on the Spacecraft Body" in *IEEE Transactions on Aerospace and Electronic Systems*, *2024,* doi: 10.1109/TAES.2024.3435176.
- Samimi H. and Uysal M.,"End-to-end performance of mixed RF/FSO transmission systems", *IEEE/OSA J. Opt. Commun. Netw.*, vol. 5, no. 11, pp. 1139-1144, Nov. 2013.
- Szajewski K., Szajewska A. " Two-way Free-space Laser Communication Earth-UAV withoutUAV emission revealing its presence" in 43-IBIMA 26-27 June 2024 Madrit, Spain.
- Weichel H., “Laser beam propagation in the atmosphere,” Proc. SPIE, vol. TT3, pp. 25–39, Aug. 1990.
- Wondmagen A. B.,Lakew D. S., Tran A. T., Paek J. and Cho S., "A Review on FSO/RF based Satellite-Aerial-Ground Communication Systems," *2024 International Conference on Information Networking (ICOIN)*, Ho Chi Minh City, Vietnam, 2024, pp. 421-425, doi: 10.1109/ICOIN59985.2024.10572075.